

Evaluation of Environment Sustainability of Clay Roof Tiles Manufacturing Practices in Sri Lanka using LCA Technique

A.K. Kulatunga, R.L. Peiris and S. Kamalakkannan

Abstract: Clay roof tiles have been one of the most utilised roofing materials in the past. With the introduction of new roofing materials, the popularity of clay roof tiles reduced over the years. However, with the modern trend towards sustainable built environment and policy decisions to ban asbestos fibre-based cement roofing tiles in Sri Lanka, demand for clay roofing tiles is positively affected. Furthermore, due to its environmentally benign performance, some of locally manufactured clay roofing tiles have gained foreign markets. However, it is rare to find any detailed study on the overall sustainability of clay roof tiles. In order to assess the environmental sustainability of the clay roofing tiles, comprehensive Life Cycle Assessment (LCA) was done from cradle to gate. Two clay roof manufacturing processes: semi-conventional and modern were considered for the evaluation. The environmental hotspots were identified through the IPCC GWP and ReCiPe analysis method using the SimaPro LCA software. Results revealed that conventional manufacturing practice is more environmentally sustainable than modern practice because modern practice causes significant influence on both impact assessment methods.

Keywords: Life cycle assessment; Sustainable manufacturing; Clay roof tile

1. Introduction

Currently, in Sri Lanka, the rise of environmental burdens in the manufacturing industries has created a growing demand for environmental awareness within the manufacturing sector. However, every product has environmental impacts over its life cycle, but the majority of manufacturers are solely focused on a profitable pursuit. Thus, it is of vital necessity to gauge the environmental sustainability of products and processes. At present, many manufacturing sectors are leaning towards the green manufacturing environment to achieve minimised manufacturing costs as well as a higher level of appreciation by society compared to its competitors in the market. Moreover, the notion of a 'Green Label' encourages manufacturers to review and account for the environmental impact of their products at each stage of the product's life cycle, from preproduction to disposal. This will increase the demand and eco-friendly image among competitors and global markets. Therefore, most of the manufacturers are expected to adapt to the Eco-labels and environmental product declaration (EPD). Hence, it increases the need for conducting proper environmental performance evaluations on products and processes while complying with the growing

sustainability concepts in order to identify the level of sustainability at a given time.

In that respect, the environmental sustainability of construction material is essential because the environmental impact of products include energy consumption, natural resource depletion, liquid discharges, gaseous emissions and solid waste generations. As a construction material, different types of roofing materials are selected to fulfil several common and specific objectives. Commonly, protection of environmental conditions like rain, wind, solar heat, snow and beast attacks are expected. In addition to that, several high-performance characteristics are expected in product quality

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aspects like less permeability, less water absorption, high heat absorption, low thermal conductivity and high impact resistance. The sustainability performance level is another crucial aspect when selecting specific roofing materials. When considering different aspects which are applied to the selection of roofing materials, environmental performances are given higher priority due to highly growing environmental pollution with industrial developments.

The energy consumption of all roofing industries constitutes intensive use of liquefied natural gas, biomass, and electricity, which is hazardous to the green environment. Thus, roofing materials being one of the most commonly utilised construction materials in Sri Lanka has created a rapidly growing demand for a comprehensive assessment of its manufacturing sustainability. Therefore, it is of paramount importance to conduct a product life cycle assessment on the roofing materials. Accordingly, the LCA is a technique that tries to identify, measure and characterise different potential environmental impacts associated with the life cycle of a product. Also, the LCA tool established by ISO 14040 and ISO 14044 is highly regarded, since it supports environmental decision making.

A comprehensive LCA analysis provides standard methods to understand the environmental sustainability performance level of roofing materials as well as assisting in bringing hidden environmental hotspots and problems to the surface. It plays a significant role in analysing environmental burden, including excessive raw material consumption, resource consumption, energy usage, inadequate waste disposal, unregulated production processes, and adverse emission discharges, amid the production environment. The ever-growing demand for the application of life cycle approaches by the highly industrialised countries is a clear indication of the potential benefits the assessment could bring about within the industrial sector. Hence, this study aims to investigate and evaluate the environmental sustainability of the clay roofing tile by comparing the two existing manufacturing practices of clay roof tile industry in Sri Lanka, which are semi-conventional and modern. Further, this study considers the hotspot identification and comparison of environmental performance within the processes of each manufacturing practice for only the cradle to gate phase.

Therefore, this comprehensive quantitative assessment will be beneficial to overcome the environmental burdens of roofing material manufactures to enhance sustainability.

2. Literature Review

The construction industry is growing exponentially more than ever due to the increasing human population and rapid globalisation. Hence they have become the biggest contender in the intensive consumption of resources and energy. Moreover, roofing materials are one of the most vital sub-cluster under construction materials. LCA is a technique which primarily aims at investigating and evaluating the potential consequences of each activity undertaken throughout the entirety of the product life cycle. Thus, environmental LCA of the product assists in evaluating the quantitative environmental sustainability. Also, it brings forward the environmental hotspots, which could be available in whatever the stages/phases of the product or processes, to enhance the sustainability of the product or process.

Based on previous studies, the LCA techniques have been used to assess the environmental sustainability for various products and processes. In that respect, the LCA was used to evaluate the environmental performance of the process currently used to package and palletise ceramic floor and wall tile and to propose and analyse improvements from an environmental point of view [5]. The study was constructed as a decision model for sustainable product design and development from product servicing in Taiwan using LCA [11]. The study focussed on examining the environmental and social impacts of Sri Lankan tea processing industry to withstand global market challenges using LCA techniques [12]. The study evaluated the potential of integrating LCA into BIM, developed and proposed an Integrated Dynamic Model using Revit, Dynamo and Excel [20]. Brundtland report mentioned that sustainability comprises three components: environment, economy and social aspects. These components or "pillars" of sustainability have to be properly assessed and balanced if a new product is to be designed or an existing one is to be improved [14].

Further, extensive studies have been carried out and discussed by using the same LCA techniques on the clay roof tiles industry to enhance sustainability. In that respect, the

research was conducted LCA towards eco-design in floor tile industry by using scenario analysis [13]. The study investigated and compared the environmental impacts of different roofing options available locally [15]. Study results reveal that modern-day construction and architecture are gradually moving towards sustainable or green building concepts.

Comparative LCA between two flooring materials has been carried out in order to identify the one with the best environmental profile and the hot spots of the two systems [16]. The study was carried out using LCA for the process of mining, treating and marketing clay in order to identify the stages and unit processes that have the most significant impact on the environment [4].

Peiris et al. [17] has performed an LCA of the production of clay roof tiles in Sri Lanka, which are made using the semi conventional method, and great importance has been given to data collected from local clay roof manufacturing industries [17]. Moreover, this study has shown the importance of reducing biomass and electricity consumption during the manufacturing process. Kurupparachchi et al. has performed an LCA of two clay roofing tiles such as clay roof and asbestos in Sri Lanka, where one uses traditional manufacturing methods, and the other follows the modern manufacturing practices, and scope was set as cradle to gate [15]. Also, a vital contribution analysis is not available in the assessment. Moreover, any decision is not made to utilise the LCA results for developing process redesign strategies. To add more to the local context, Abeyesundara et al. conducted a research study to compare the environmental, economic, and social impacts of two types of roofing elements in Sri Lanka; roof tile and asbestos using LCA methodology [1].

Besides, there exist LCA studies conducted for different ceramic roof materials in a global context. In these studies, the environmental performance of several flat roof systems with different materials and insulation thicknesses using LCA are compared [2, 6, 7, 8]. In that respect, the benefit of the green roof was evaluated [19]. Also, the LCA has been used to evaluate the environmental damage from three concrete flat roof technologies in Israel [18].

The literature review reveals that there is only a handful of research focusing on LCA

application on roof tiles in Sri Lanka [1, 17]. Further, these studies focus on the application of LCA in the Sri Lankan ceramic tiles industry and semi-conventional roof tile industry with comprehensive discussions on the environmental impacts of ceramic products at various stages of the production process [9, 17]. However, to our knowledge, no author has yet published a comprehensive LCA analysis to evaluate the quantitative environmental sustainability of the clay roof tile manufacturing in the local context. This study aims at filling this gap by evaluating the quantitative environmental sustainability of the clay roofing tile, by comparing the two existing manufacturing practices, which are semi-conventional and modern. Also, this study considers the hotspot identification and comparison of environmental performance within the processes of each manufacturing practices. Therefore, it will be beneficial to overcome environmental burdens and to understand the sustainability level of clay roofing material.

3. Methodology

To identify environmental hotspots and to compare different manufacturing practices, LCA methodology was used. LCA, which is established by ISO 14040 and 14044, is a useful tool in evaluating environmental performance comprehensively. It employs LCA within the cradle to gate phase. The ISO standards provide the methodological framework of LCA and the explicit guidance on conducting a proper LCA. The LCA framework consists of four major steps, namely, goal and scope definition, inventory analysis, impact assessment, and interpretation, as shown in Figure 1. Further, the LCA software SimaPro (Ph.D. version) which is connected with the global impact database, was used to calculate the environmental impact for both mid-point (Problem-oriented) and end-point (Damage oriented) levels by using different impact methods such as IPCC 2013, ReCiPe, and Ecoindicator99. The Functional Unit (FU) of this assessment was considered as roof tile to cover 1 m². Further, life cycle inventory preparation and environmental impact calculation were done based on FU.



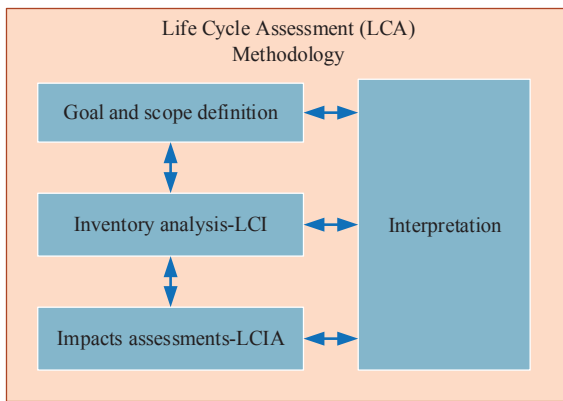


Figure 1- LCA Methodology Framework- ISO14040

- **Goal and Scope Definition:** Phase of goal and scope define what the purpose of the study is, the intended use of the results and what should be included.
- **Life Cycle Inventory (LCI):** Phase of life cycle inventory involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.
- **Life Cycle Impact Assessment:** Phase of life cycle impact assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.
- **Interpretation of results:** Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope to reach conclusions and recommendations.

3.1 Manufacturing practices of study

In this study, semi-conventional practices and modern practices are considered. The differences between the two practices with respect to each one of the main unit processes are listed in Table 1 below.

3.2 Goal and scope definition

The ultimate goal of this comparative LCA study is to benchmark the sustainability of two types of practices in clay roof tile manufacturing and, to evaluate the sustainability effectiveness of modern practice in comparison with the conventional practices. Since cradle to gate approach is considered, only pre-manufacturing and manufacturing phases were chosen as the scope and boundary of this LCA.

Roof tiles are primarily designed to cover the top, enclosing the space inside of a building. Thus, the functional unit of a 'clay roof tile' product is defined as "the effective unit area covered by roof tiles" (The roof tile required to cover 1 m²) which is similar to the case of semi-conventional practice. This unit can be used as a standard measure for any roofing material more conveniently than using a single roof tile or unit weight of a roof tile as the measurement unit. Specifications of roof tiles are different while comparing each other. Accordingly, an area of 1 m² of the top surface was considered as the FU. All the data collected for parameters were transformed into the FU to calculate the average monthly production of roof tiles. The goal and scope definition is presented in Table 2.

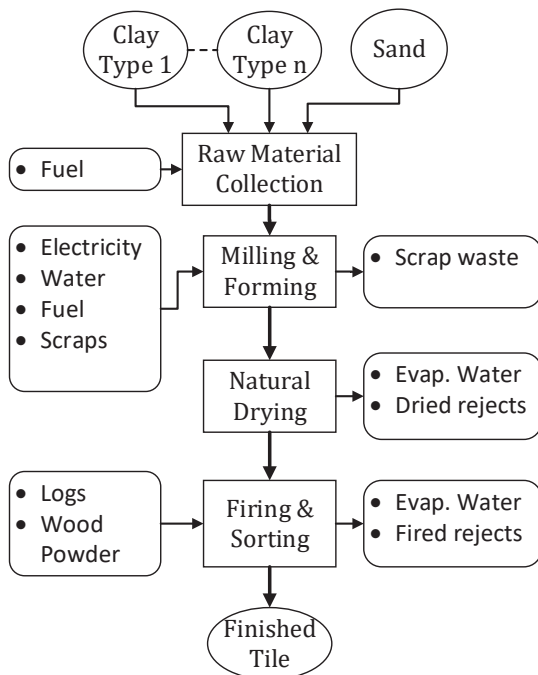
Table 1 - Process Differences between two Different Practices

Process	Types of manufacturing practices	
	<i>Semi-conventional</i>	<i>Modern</i>
Raw material collection	Excavation - Excavator Transport - Tipper/Lorry	Excavation - Excavator Transport - Tipper/Lorry
Milling & forming	Electrical Machines (Ex. Pug Mills) Forming - Extruders and presses	Electrical Machine (Ex. Roller Mills) Forming - Extruders and presses
Drying	Natural Drying	Natural Drying Hot air drying (By hot air gen. or kiln exhaust)
Firing	Bio-mass kilns	Fossil fuel-fired kilns (ex: LP Gas, Diesel)

Table 2 - Goal and Scope Definition

Definition	Description
Goals	<ul style="list-style-type: none"> • Benchmarking of both roof tile manufacturing practices • Identification of environmental impacts and hotspot.
Scope	Cradle to gate
Functional unit	1 m ² of clay roof tile
Life cycle level-based boundary	<ul style="list-style-type: none"> • Life cycles of infrastructure and capitals were neglected. (Ex: Manufacturing of extruder) • Non-material emissions(Ex: Noise) were neglected. • Long term emissions were considered.

Semi-Conventional Type



Modern Type

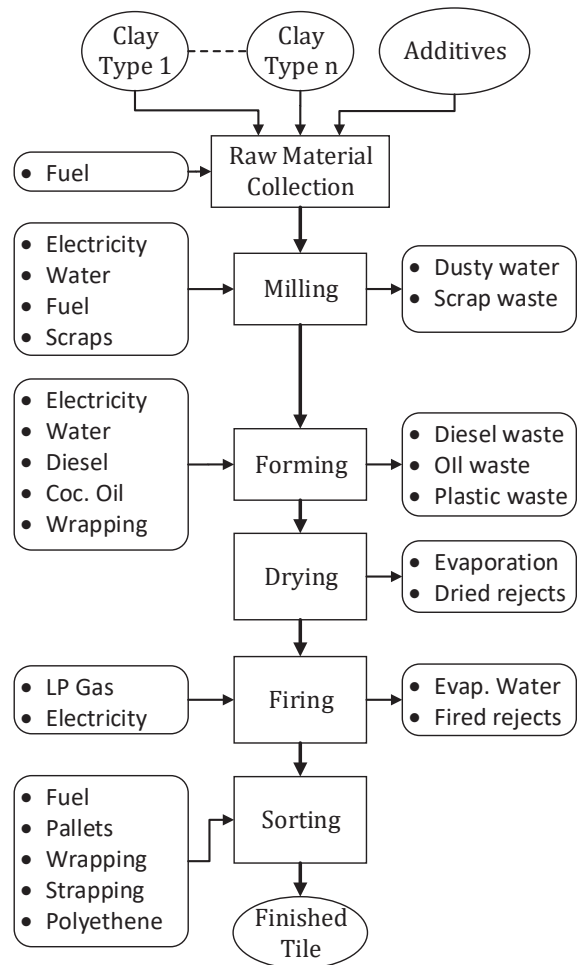


Figure 2 - Process Flow Diagram (PFD) - Semi-conventional and Modern Manufacturing Practices

3.3 Life Cycle Inventory

The life cycle inventory is the collection of data consisting of all the input materials, energies, and all the other related data. In order to prepare the LCI, the process flow diagram comprising of all the inputs and outputs during the entire production process is developed. The generalised process flow diagram of both semi-conventional and modern manufacturing

practices has been presented in Figure 2. All the measures were taken in relation to the FU. Inputs exhibit the contribution of energies and additional resources for each unit process, and the main material flow and waste stream were also presented. The LCI data was collected through recorded data, direct measurements, site visits, and direct contact with technical officers, as well as our research team have



constructed the country-specific computerised model in SimaPro [17] for electricity and petroleum supply. That model has been used for linking with primary data.

3.4 Life Cycle Impact Assessment (LCIA)

It is important to note that the Life Cycle Impact Assessment (LCIA) under LCA, aims at analysing the potential environmental complexities that are triggered by technological interventions into ecological balance. The final step of the LCA methodology involves the interpretation of LCI and LCIA stages in order to find hot spots and compare alternative scenarios [3]. Further, it will also appraise the impact on human health, natural environment, and ecosystem. In order to assess the impact, the specialised LCA software called "SimaPro" is used in this analysis. The software is used to evaluate data based on other impact categories such as acidification, respiration, climate change, radiation, ozone depletion, acidification and human toxicity which are usually too complex to analyse manually. It is important to note that LCA and the impact assessment analyse the potential environmental impacts that are caused by interventions. These interventions cross the border between technosphere and ecosphere and act on the natural environment and humans, often only after exposure steps [10].

4. Results and Discussion

Based on the LCI data, the LCI analysis and impact assessment was carried out. Using the "SimaPro" software, computerised environment impact model for the production of roof tiles manufacturing practice was constructed. In this model, processes are modified by replacing country-specific back life cycles (Ex: Fuel, Electricity) to achieve accuracy. Finally, the whole process is reviewed to avoid probable double-counting errors due to overlapping of system scopes. After completing the computerised impact model, environment impact levels are interpreted in different aspects and benchmarked against each other. LCIA was done by comparison mode using the following methods.

- > IPCC GWP 100a
- > ReCiPe - Endpoint (Damage assessment)

IPCC 2007 GWP 100a V1.02 method indicates the level of global warming potential as a result of greenhouse gas (GHG) emissions. All

significant GHG emission sources were taken into the calculation by considering the scope of the product life cycle.

ReCiPe method indicates the extents of adverse impacts in categories such as human health, ecosystem quality, and resources. The severity of various diseases and the extent of reduced the life span of human beings are the primary factors in evaluating human health, while degrees of damage to the ecosystems through human toxicity, ozone depletion etc. are the primary factors in assessing the ecosystem quality. Depletion of natural resources such as minerals, and fossil fuel consumption will be calculated under resources aspect.

4.1 LCI Analysis

The primary and secondary LCI data from the field visit was analysed and summarised. Table 3 and Table 4 show a life cycle inventory data of semi-conventional practice and modern practice, respectively, for one square meter (1m²) of clay roof tile which is defined as a functional unit of this study. LCI data was collected by site visits, recorded data, direct measurements, and direct contact with technical officers. This summarised LCI data was used to model and assess the environmental potential through the SimaPro software.

According to comparative LCI results from Figure 3, modern practice shows higher consumption in many resource categories such as fuel and electricity. While comparing with semi-conventional practice also, the amount of rejected scraps is also higher than comparing semi-conventional because of kiln usages and electricity machinery operations. When considering the main raw material and water usages are approximately equivalent for both practices.

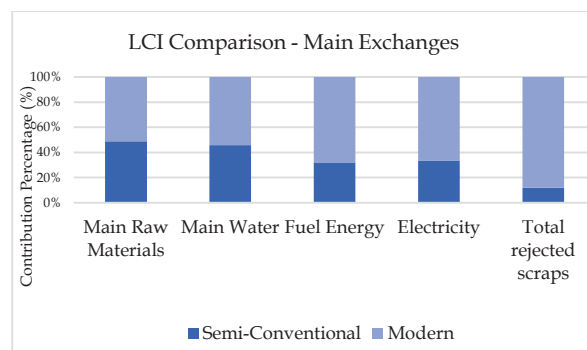


Figure 3 - LCI Comparison

Table 3 - LCI Summary Report - Semi-Conventional Type Manufacturing

Exchange Type	Resource	per FU		Section-wise Allocation (%)				
		Unit	Value	MN	M/F	ND	F/S	WS
Main Material	Main clay materials	kg/m ²	51.79	100				
	Water	kg/m ²	13.22		100			
Energy	Biomass: Wood logs	m ³ /m ²	0.0277				100	
	Biomass: Wood powder	kg/m ²	4.68				100	
	Electricity	kWh/m ²	1.872		100			
Disposals & Emissions	Drier rejects (Recycle)	kg/m ²	9.33			100		
	Fired rejects (Landfill)	kg/m ²	0.32					100
	Evaporated water	kg/m ²	14.77			66.4	33.6	
Overall Transport	Road transport	kg/m ²	4.297					
	Diesel (Transport)	kg/m ²	0.034		100			

[MN-Main material flow, M/F-Milling & Forming, ND-Natural Drying, F/S-Firing & Sorting, WS-Waste Scenarios]

Table 4 - LCI Summary Report - Modern Type Manufacturing

Exchange Type	Resource	per FU		Section-wise Allocation (%)						
		Unit	Value	M	PR	SC	FM	D/F	ST	DP
Main Material	Main clay	kg/m ²	51.7	100						
	Reused clay	kg/m ²	2.9	100						
	Crushed powder	kg/m ²	2.9	100						
	Water	kg/m ²	21.0		92.1	6.6	1.3			
Auxiliary Material	BaCO ₃	kg/m ²	0.0		100					
	Coconut oil	kg/m ²	0.0				100			
Energy	LP Gas	kg/m ²	4.2					100		
	Diesel	kg/m ²	0.0	20.2	19.5	9.0	40.1		11.2	
	Electricity	kWh/m ²	3.6		24.2	29.4	11.7	34.7		
Packaging Material	Shrink wrapping	kg/m ²	0.1				77.6		22.4	
	Wood pallets	kg/m ²	1.7						100	
	Strapping	kg/m ²	0.0						100	
	Black polythene	kg/m ²	0.0						100	
Disposals & Emissions	Body-mix rejects	kg/m ²	34.5				100			
	Drier rejects	kg/m ²	24.2					100		
	Fired rejects	kg/m ²	9.2						31.3	31.3
	Dusty water	kg/m ²	2.1							100
	Coconut oil	kg/m ²	0.0							100
	Diesel	kg/m ²	0.0							100
	Evap. water	kg/m ²	16.8							100
	Plastic waste	kg/m ²	0.1							100
Overall Transport	Road transport	tkm/m ²	1.9							
	Ocean transport	tkm/m ²	391.2							

[M-Main material flow, PR-primary section, SC-Secondary section, FM-Forming section, D/F-Drying/Firing, ST-Sorting, DP-Disposal]

4.2 LCIA- IPCC 2007 GWP 100a Analysis
Global Warming Potentials (GWPs) are used to quantify the measure of the globally averaged relative radiative forcing impact of certain greenhouse gas. It is defined as the cumulative radiative forcing of direct and indirect effects integrated over some time, from the emission of a unit mass of gas relative to reference gas (Carbon dioxide (CO₂eq)). Further, the GWPs

provide a standard unit of measure, which allows analysts to add up emission estimates of different gases and allows policymakers to compare emission reduction opportunities across sectors and gases [21].

Figure 4 shows the section-wise comparison for modern practice. The graphs provide a qualitative comparison among different available categories. All values were evaluated



with respect to the maximum impact, which was set as 100%. It is evident from Figure 4 that the drying and firing process (19.2 kg CO₂(eq)) has the most significant potential impact on global warming due to Liquid Petroleum Gas (LPG) usage. Further, it shows that impact of drying and firing are ten times greater than the other processes.

Liquefied petroleum gas (LP-gas) consists of propane, propylene, butane, and butylene which is used to produce heat in industries and it produces Greenhouse gasses (GHG) such as Carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) emissions during LPG combustion process. However, this fossil fuel combustion processes rapidly increase the level of GHG emissions in the atmosphere, causing global warming and climate changes.

Figure 5 shows the section-wise comparison of GWP for semi-conventional practice. According to GWP graphs, the firing process (1.84 kg CO₂(eq)) has a significant GWP towards the environment than the other sectors due to biomass usage. Biomass is the main energy source used in "Firing" section. When considering the entire life cycle of firewood, it comes from nature as trees in the forest, and goes back to nature as wood combustion emissions such as carbon dioxide and sulphur dioxide gases. When considering the combustion process of firewood, it generates significant GWP by emitting greenhouse gases. The consumption volume of the firewood is the main parameter of determining GWP by firewood consumption.

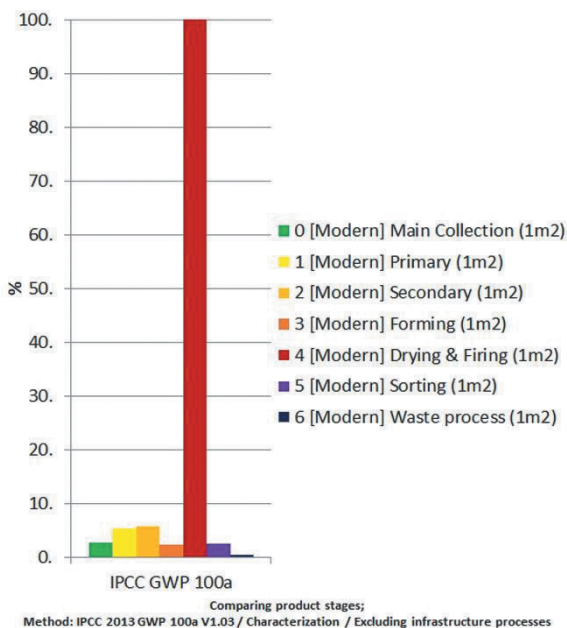


Figure 4 - Section-wise GWP-Modern Practice

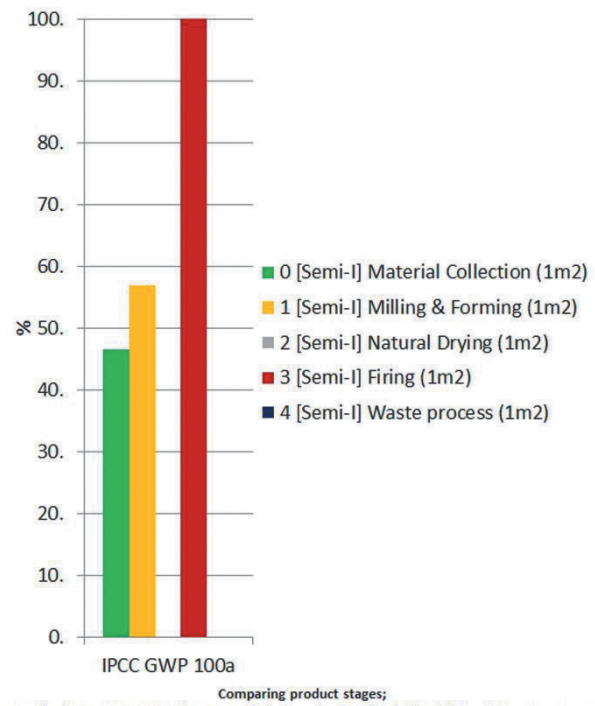


Figure 5 - Section-wise GWP-Semi-conventional practice

The second most GWP contributor is milling and forming process due to electricity consumption.

In this section, only electricity and water are used as input exchanges. When considering several high electrical power-consuming machines like pug mills, extruders, hydraulic presses and high GWP in electricity generation, electricity supply can be identified as the main source for impacts. Machines are operated a number of hours to process materials. When considering material re-processing of rejects and recycled scraps, additional electricity is consumed to produce unit output. In most of the semi-conventional roof tile manufacturing practices, industrialists are using outdated machinery. In this manner, there is a high possibility for obtaining low electrical efficiency than standard ratings.

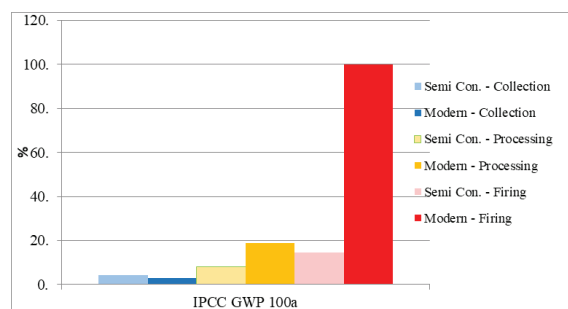
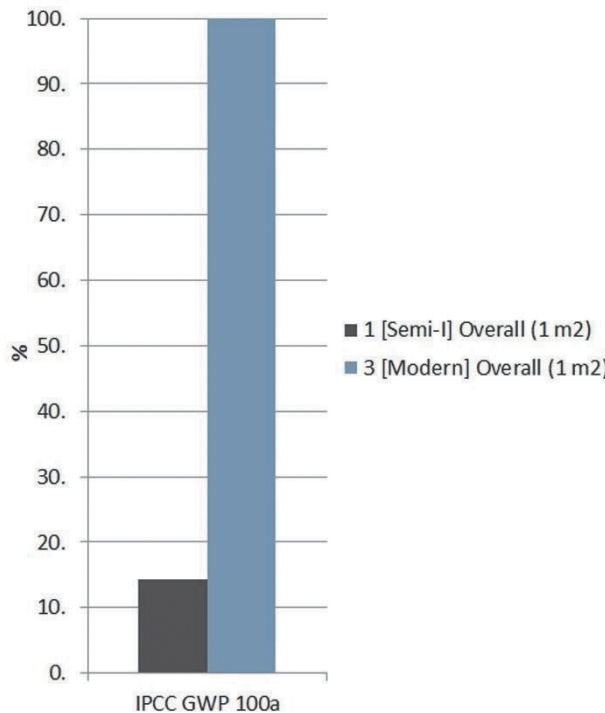


Figure 6 - Section-wise GWP Comparison for both Semi-conventional and Modern Practice

Figure 6 illustrates the section-wise GWP comparisons between both semi-conventional and modern practices. It emphasises that the firing process (19.2 kg CO₂ (eq)) from modern practice has a significant potential impact on global warming than other processes due to significant LPG usage as well as its impacts towards the environment.



Comparing 1 p '1 [Semi-l] Overall (1 m2)' with 1 p '3 [Modern] Overall (1 m2)'; Method: IPCC 2013 GWP 100a V1.03 / Characterization / Excluding infrastructure processes

Figure 7 - Overall GWP Comparison between Semi-conventional and Modern Practice

Figure 7 Illustrates the overall GWP contribution to the environment between both semi-conventional (3.79 kg CO₂(eq)) and modern practice (22.6 kg CO₂(eq)). It can be observed that modern practice has the highest significant potential impact on global warming to the environmental impact. It is due to LPG usage because, according to the above results, it seems obvious. Heat generation process generates a large quantity of GHG emissions to the air. Even though GHG emissions are produced along the product life cycle of LPG, it is not significant compared to the heat generated at the end of the life cycle.

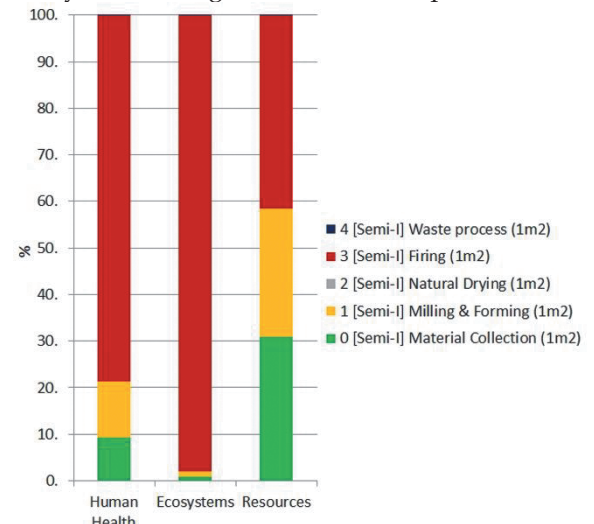
Hence, in order to reduce the GWP from modern clay manufacturing, several doorways can be installed for an eco-design strategy to reduce greenhouse gas emissions through the

product life cycle of clay roof tile and it is mentioned below.

- Product Enhancement
 - Optimising properties of green tile and desired final tile
 - Reduction of capability to waste products
- Enhancement drying & firing process
 - Enhancement of alternative fuel
 - Reduction of LP gas consumption
 - Reduction of heat wastage
 - Heat recovery techniques

4.3 LCIA-ReCiPeAnalysis

ReCiPe method consists of several environmental impact measurements in different aspects. In that respect, ReCiPe Endpoint analysis shows an aggregated result of midpoint impact categories to three categories called as human health damage, ecosystem damage and resource depletion.

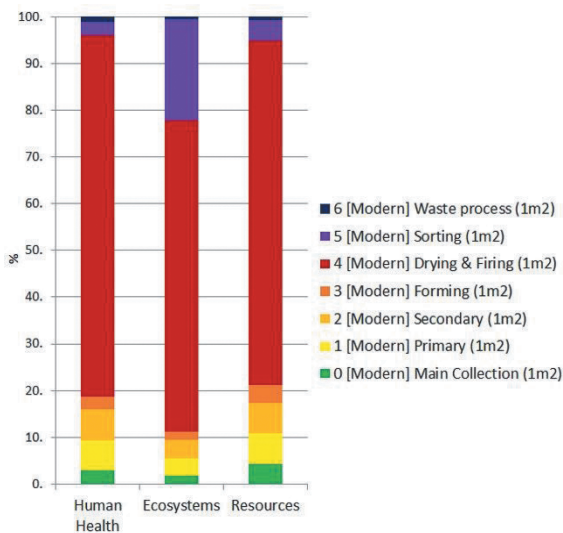


Analyzing 1 p 'Semi-l] Analyze'; Method: ReCiPe Endpoint (H) V1.13 / Europe ReCiPe H/A / Damage assessment / Excluding infrastructure processes

Figure 8 - Section-wise Endpoint ReCiPe Impact - Semi - conventional Practice

Figure 8 illustrates the ReCiPe single score damage assessment for semi-conventional practice. Based on the single score impact assessment result, the major contributor to the environmental impact is the firing process. The human health category (0.21Pt) and ecosystem (1.21 Pt) are affected significantly due to the high firewood consumption in the firing process—moreover, the resource category affected by milling and forming process and material collection.

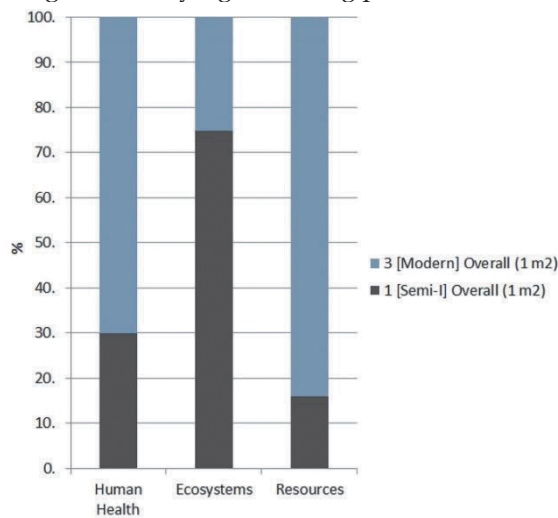




Analyzing 1 p '[Clad-Mfg][Clay-Modern]Overall-with waste (1m2)'; Method: ReCiPe Endpoint (H) V1.13 / Europe ReCiPe H/A / Damage assessment / Excluding infrastructure processes

Figure 9 - Section-wise Endpoint ReCiPe Impact - Modern Practice

Figure 9 shows the ReCiPe single score damage assessment for modern practice. It is evident from the results of single score impact assessment result, the major contributor to the environmental impact is the drying and firing process in all three endpoint impact categories human health (0.601 Pt), ecosystem (0.337 Pt) and resource (0.317 Pt) due to the high LPG usage in the drying and firing process.



Analyzing 1 p 'Analyze Overall - Semi-I/Modern (1 m2)'; Method: ReCiPe Endpoint (H) V1.13 / Europe ReCiPe H/A / Damage assessment / Excluding infrastructure processes

Figure 10 - Overall Endpoint ReCiPe Impact between Semi-conventional and Modern Practices

Figure 10 shows the ReCiPe, a single score damage assessment between both semi-conventional and modern manufacturing practices. The human health (0.753 Pt) category and resource category (0.403 Pt) are affected significantly by modern practice due to the high LPG consumption in modern practice. However, the ecosystem (1.24 Pt) affected significantly by semi-conventional practice

because deforestation by collecting firewood can be considered as the reason for more ecosystem damage rather than fossil fuel combustion. The LCIA summary of both manufacturing practices is shown in Table 5.

Table 5 - LCIA Summary of clay roof tile practices

Method	Indicator	Semi-conventional practice	Modern practice
IPCC GWP	GWP	Low (3.79 kg CO ₂ (eq))	High (22.6 kg CO ₂ (eq))
ReCiPe	Human health	Low (0.295 Pt)	High (0.753 Pt)
	Ecosystems	High (1.24 Pt)	Low (0.485 Pt)
	Resources	Low (0.099 Pt)	High (0.403 Pt)

5. Conclusion

The long-term sustainability of the manufacturing industries depends upon technological improvement, green production and sustainable energy because global warming is the biggest threat to the world in the current period. A comprehensive LCA can effectively evaluate the quantitative sustainability level of products or processes, and bring out concealed environmental hotspots to the surface which will in return play a major role in environmental impacts and comparing the environmental performance among different technology-based manufacturing practices. According to the comparative LCIA results, modern practice makes a higher impact in many aspects when compared with semi-conventional practice. According to the IPCC GWP impact assessment method, the firing process was identified as the environmental hotspot for both manufacturing practices. Drying and firing process discharges high amounts of emission in the context of the modern practice, approximately seven times more than semi-conventional practice due to excessive LPG combustion because the LPG combustion processes rapidly increase the level of GHG emissions in the atmosphere and cause global warming and climate changes. Based on the section wise ReCiPe damage assessment, all three end point categories are affected predominantly by the drying and firing process in both modern and semi-conventional practices. Further, when concentrating on the overall ReCiPe impact method, modern practice acts as a major contributor to the environmental impact in both impact categories human health and resources. Hence, Semi-conventional practice shows more impact only in the aspect of eco-system damage since the deforestation by collecting firewood is considered as the main reason for a greater eco-system damage

Table 6 - Key Factors of Environment Hotspots - Semi-Conventional Type

Hotspot	Source	Contribution	Reasons for higher impacts
Firing	Firewood	Main	<ul style="list-style-type: none"> ○ week selection of trees for felling ○ lack of sustainable re-forestation ○ high energy consumptions in sawmilling ○ Lack of firewood and heat optimisation ○ Harmful emissions during combustion
Milling & Forming	Electricity	Significant	<ul style="list-style-type: none"> ○ Upstream life cycle emissions of electricity ○ Additional energy requirement for recycling ○ Lack of electrical energy optimisation

Table 7 - Key Factors of Environment Hotspots - Modern Type

Hotspot	Source	Contribution	Reasons for higher impacts
Drying & Firing	LP Gas	Main	<ul style="list-style-type: none"> ○ Upstream life cycle emissions of electricity supply ○ Lack of LP gas and heat optimisation in the combustion process ○ Harmful emissions during combustion
Primary & Secondary Milling	Electricity	Significant	<ul style="list-style-type: none"> ○ Upstream life cycle emissions of electricity supply ○ Additional energy requirement for recycling ○ Lack of electrical energy optimisation
Sorting	Thermoplastic Packaging Materials	Significant	<ul style="list-style-type: none"> ○ Upstream life cycle emissions of thermoplastic packaging materials ○ High consumption and non-reusing of packaging materials

rather than fossil fuel usage. Based on this environmental sustainability assessment, the hotspot, source, contributor and the reasons are concluded for both practices as shown in Table 6 and Table 7. It can guide researchers to enhance the environmental sustainability of clay tiles.

Hence, this study reveals that the sustainability of modern practice is essential as it plays a major role in harming the environment compared to semi-conventional practice. In order to overcome these adverse environmental challenges, eco-design capabilities such as reduction of LPG consumption, reduction of firewood consumption, enhancement of heat generation process, and reduction of waste generation can be identified from the comprehensive assessment. Therefore, it is necessary to undertake environmental design based measures to improve the sustainability of the Sri Lankan clay roofing industry.

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